

Why we need to see the dark matter to understand the dark energy

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Abstract. The cosmological concordance model contains two separate constituents which interact only gravitationally with themselves and everything else, the dark matter and the dark energy. In the standard dark energy models, the dark matter makes up some 20% of the total energy budget today, while the dark energy is responsible for about 75%. Here we show that these numbers are only robust for specific dark energy models and that in general we cannot measure the abundance of the dark constituents separately without making strong assumptions.

1. Introduction

We cosmologists are very proud that our field has finally reached the status of “precision science” over the last decade. The quality of the current observations of the cosmic microwave background (CMB), the galaxy distribution and the luminosity distance to type Ia supernovae (SN-Ia) is indeed impressive, and has allowed the construction of a concordance model in which the universe contains the known, baryonic, matter (5% of the energy density today), radiation (negligible energy density today), dark matter (20%) and dark energy (75%).

The need for dark matter became apparent long ago in order to explain the motion of galaxies in clusters [1] and the observed galaxy rotation curves. In cosmology, it is often modelled as a pressureless fluid with negligible interactions. Much more recently, less than ten years ago, new SN-Ia data [2] convinced the majority of cosmologists that dark energy was needed as well. Until today the nature of the dark energy is a deep mystery. Although many models have been proposed, there are none that can explain its current abundance in a natural way. The alternative to the model building is a more phenomenological approach, where one measures the physical properties of the dark energy. To this end, one introduces a completely general fluid and tries to determine its characteristics from observations.

2. The dark degeneracy

Unfortunately there is a fundamental problem in this approach. Let us illustrate this by considering only a perfectly homogeneous and isotropic universe with vanishing spatial curvature. In this case the line element is

$$ds^2 = -dt^2 + a(t)^2 dx^2 \quad (1)$$

with only one degree of freedom, the scale factor $a(t)$, or equivalently the Hubble parameter $H(t) = \dot{a}/a$. The energy-momentum tensor has to be compatible with perfect homogeneity and

isotropy, which means that it has to have the form of a perfect fluid,

$$T_{\mu}^{\nu} = \text{diag}(-\rho(t), p(t), p(t), p(t)). \quad (2)$$

There are two degrees of freedom in the energy momentum tensor, $\rho(t)$ and $p(t)$. The 0-0 Einstein equation for this simple example leads to

$$H^2 = \frac{8\pi G}{3}\rho \quad (3)$$

called the Friedmann equation. This equation links the behaviour of $a(t)$ with the behaviour of $\rho(t)$. The covariant conservation of the energy momentum tensor gives

$$\dot{\rho} = -3H(\rho + p). \quad (4)$$

We find therefore that the pressure p describes the physical properties of the fluid. Once it is given, then the two equations can be integrated and solutions for H and ρ are found. Often cosmologists parametrise the pressure via an auxiliary function w through an equation of state

$$p = w\rho. \quad (5)$$

Although the equation of state is often written in implicit form as $p = p(\rho)$ this is not always possible, for example if we are dealing with one effective fluid composed of two fluids, see e.g. [3] for an explicit example. For this reason w is often taken to be a free function of time.

Our original goal of measuring the dark energy properties is now reduced to the problem of determining the equation of state parameter of the dark energy, w_{DE} (the dark matter being characterised by $w_m = 0$). Introducing additionally the quantity Ω_m for the relative energy density in matter (both baryonic and dark) today, and using the redshift z instead of t as the time variable, it is easy to combine the equations (3) and (4) and to derive an explicit expression for the equation of state parameter,

$$w_{\text{DE}}(z) = \frac{H(z)^2 - \frac{2}{3}H(z)H'(z)(1+z)}{H_0^2\Omega_m(1+z)^3 - H(z)^2}, \quad (6)$$

with $H' = dH/dz$ and $H_0 = H(z=0)$. It appears that perfect knowledge of H implies perfect knowledge of w . Unfortunately this is only true if we also know Ω_m . But cosmological observations like the luminosity distance only measure $H(z)$, and cannot give any independent constraints on the matter abundance. We can therefore only determine a one-parameter family for w_{DE} as long as we do not have an independent measurement of Ω_m , e.g. from astroparticle observations and/or collider measurements. This has been noticed before (see e.g. [4]) but seems to have been forgotten within the community.

3. Perturbation theory and the CMB

Our universe is not perfectly isotropic and homogeneous, so is it possible that this dark degeneracy can be broken by studying e.g. CMB temperature anisotropy measurements? The short answer is “no”. The full Einstein equations for our model can be written as

$$G_{\mu\nu} = 8\pi G \left(T_{\mu\nu}^{(m)} + T_{\mu\nu}^{(\text{DE})} \right). \quad (7)$$

Clearly the split of the energy-momentum tensor on the right-hand side is arbitrary. Only the sum of the two tensors is determined by any measurement involving only gravity (which depends on the geometry, described by the left-hand side). By allowing a fully arbitrary $T_{\mu\nu}^{(\text{DE})}$,

any further unknowns cannot be determined. This concerns not only Ω_m , but also any possible couplings between the dark quantities, and of course also possible splits into more than two dark fluids. All these things *cannot* be measured by cosmological probes. If we (have to) allow for a fully general dark (energy) component, then for all practical purposes we have to limit ourselves to a single general dark component. Only non-gravitational measurements can give us information that goes beyond this description.

It is therefore very worrying that although many papers have been published putting constraints on $w(z)$, seemingly no-one has found the degeneracy in their data analysis. There is really no excuse for groups who have used only distance data. The most likely explanation is that the parametrisations used were not flexible enough to exhibit the presence of the full family of solutions. This illustrates once more that one has to be extremely careful not to put in by hand what one wants to measure.

However, things become more subtle when also including CMB data, as now we have to look at perturbation theory. The theory of general fluids in first order perturbation theory is well known, see for example [5] or [6]. One finds (in Newtonian gauge, say) that in addition to w two new variables appear which characterise the physical properties of the fluid, the pressure perturbation δp and the anisotropic stress Π . For reasons of brevity and simplicity we will not discuss the anisotropic stress here further (and set it to zero), but we cannot avoid taking a closer look at δp .

Since we know that a cosmological constant is a good fit to the data (see e.g. [7]) we construct a family of models that is degenerate with Λ CDM. For the equation of state parameter we use (see [8])

$$w_{\text{DE}}(\lambda; z) = \frac{-1}{1 - \lambda(1+z)^3}. \quad (8)$$

The cosmological constant has no perturbations, and those of the dark matter are characterised by $\delta p = 0$. Therefore the sum of the two still obey the same condition we set $\delta p = 0$ overall. Using the WMAP3 CMB data [9] and the SNLS SN-Ia data [10] we find the result shown as the filled contours in the left panel of Fig. 1. Clearly, even using CMB data, it is impossible to pin down Ω_m . This is shown explicitly in the right panel of Fig. 1 where we show three CMB power spectra along the degeneracy (solid curves), computed for $\Omega_m = 0.1, 0.25$ and 0.6 . They all agree with the binned data and are practically indistinguishable.

But the most common dark energy model, quintessence, uses a scalar field. The pressure perturbation of a scalar field is characterised by $\delta p = \delta \rho$ in its rest frame. This means that the scalar field dark energy cannot cluster on small scales because of pressure support. The difference in δp makes it possible to distinguish the two dark components, and now the data allow to measure Ω_m , as shown by the open contours in Fig. 1 and the dashed CMB power spectrum for $\Omega_m = 0.1$ which does not agree with the data. However, we do not actually *know* the pressure perturbation of the dark energy, nor have we measured it. We have just fixed it by hand.

4. Conclusions

We have seen that cosmology cannot measure separately the properties of the dark matter and of a general dark energy component. In order to do that, we either need to impose additional assumptions, for example that the dark energy is a scalar field, or else we need a non-gravitational measurement of the dark matter properties, specifically of its contribution to the total energy density of the universe. One possibility is a detection of supersymmetry at LHC, which may in turn determine the abundance and mass of the lightest stable SUSY particle, one of the best candidates for the dark matter.

As a corollary, if the abundance determined in this way is not the one expected within the Λ CDM cosmological concordance model, one possible explanation is an evolving dark energy.

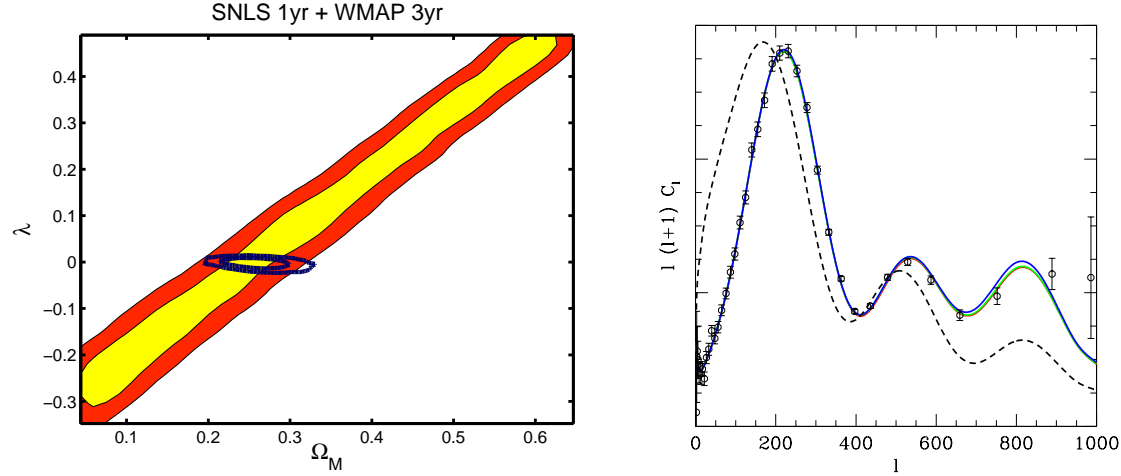


Figure 1. CMB and SN-Ia data cannot measure Ω_m for general dark energy models: In the left panel we plot filled contours at 1σ and 2σ limits for a model with $\delta p = 0$, while the open contours show the limits for scalar field dark energy. The right panel shows the corresponding CMB power spectra together with the binned WMAP3 data (solid curves for $\delta p = 0$ and dashed curve for a scalar field model with $\Omega_m = 0.1$).

We can also consider the degeneracy as a test of the generality of the different approaches to measure the dark energy equation of state. Since no analysis so far seems to have found it, we can only wonder what else has been overlooked.

Finally, although we show here that one never can prove experimentally from cosmological data alone that the dark energy is a cosmological constant, it is remarkable that a model containing just cold dark matter and Λ fits the data so well. From a model selection point of view Λ CDM is still the preferred model because of its simplicity.

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